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Solar photovoltaic and thermal technology and applications in China

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ABSTRACT

The interest in research and development of solar PV and thermal applications has been growing fast in China due to climate change concerns and environmental protection in addition to energy shortage. A number of research achievements have been put into practice, and a promising solar energy market has been formed. Among them, solar water heaters (SWHs), photovoltaic (PV) cells, PV power generation, and PV/thermal (PV/T) systems have gained the most popularity. This work reviews the solar energy resources, PV technology and applications, development of solar thermal applications, and the research and development of PV/T systems in China. The results show that China's renewable energy applications have grown rapidly in the past 10 years, and that China has become the biggest producer of PV cells and SWHs in the world. In 2011, China's PV products held 42% and the SWH cumulative installations constituted about 2/3 of globe amount. One trend in SWH development in China is the integration of the SWHs with the building structure, and PV/T hot water systems are expected to dominate solar applications in buildings. Problems lying in China's PV industry are pointed out, and suggestions for solving the problems are proposed.

Contents

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1. Introduction

Public awareness of energy crises in the 1970s stimulated a great deal of interest in research, development, and applications of solar energy in China. The interest has been fast growing in the past decade due to energy shortage and climate change concerns. China has pursued aggressive policies to boost the use of renewable energy. “The Renewable Energy Law of the People's Republic of China” took effect on January 1, 2006. The law urges local governments to establish policies stipulating development and applications of renewable energy, among which solar energy is an important element. Since then, a number of laws and regulations have been promulgated, such as “Energy Conservation Law”, “Medium and Long-term Development Plan of Renewable Energy” and “Civil Buildings Energy Saving Ordinance” [1,2].

To effectively implement the Renewable Energy Law of the People's Republic of China, several nationwide and many provincial level and municipal level renewable energy development funds, financial subsides, and incentives in interest rate and tax reduction have been established, of which some are specific for solar energy developments and applications. In 2006, Chinese Ministry of Finance (MOF) and Ministry of Housing and Urban–Rural Development jointly issued “Measures on the Administration of Specific funds for Renewable Energy Developments” and “Provisional Measures on the Administration of Specific Funds for Applications of Renewable Energy Buildings”. In 2009, MOF issued the “Provisional Measures on the Administration of Financial Subsidies for Solar Photovoltaic Buildings” [4], and MOF and Ministry of Scientific and Technology (MOST) jointly issued “Provisional Measures on the Administration of Financial Subsidies for Golden Solar Program” [3]. China has become the world's biggest investor in renewable energy sources. In 2011, China invested 52 billion US dollars in renewable energy sources, amounting to near 1/5 of the world total investment and outranking every other country [5]. There were 581 demonstration projects, 47 demonstration cities and 98 demonstration counties for renewable energy utilization at the end of 2010 [2].

The renewable energy usage constituted around 8% of the total energy consumption in China in 2011. Chinese government has an agenda to increase the renewable energy proportion to 15% in 2020, with solar energy playing an important role [6]. This work provides a comprehensive review of the solar energy resources and the status of development and applications of solar PV and thermal applications in China, including PV cells, SWHs, solar buildings, solar cookers, and PV/thermal systems. This review offers people a rigorous understanding of the development and applications of China's solar energy technology. The work also analyses the problems lying in China's PV industry, and suggests measures for solving the problems.

2. Solar energy resources and energy demands in China

2.1. Solar energy resources

China has abundant solar energy resources. It is estimated that the dry land surfaces of China receive solar energy about 50×10^{12} GJ/yr. The solar radiation in China ranges from 3.35 to 8.37 GJ/ m^2 yr and can be divided into five zones as listed in Table 1. The main characteristics of the regional distribution of solar energy resources are as the following:

(1) More than two-thirds of China receives an annual total solar radiation exceeding 5 GJ/m^2 with more than 2200 h of sunshine a year.
(2) The area with the maximum total solar radiation is in Qingzang Plateau, and that with the minimum total solar radiation is in Sichuan Basin, both in the northern latitudes of 22°–35°.
(3) The west part of China has higher total solar radiation than the east part, and except Tibet and Xinjiang the southern area generally has less total solar radiation than the northern area.
(4) The geographical distribution of solar resources does not coincide with the national power load profile. In the desert and plateau areas, the solar resources are abundant, but the power demand is relatively smaller. On the contrary, the coastal regions with heavy power loads have insufficient solar resources. This presents a significant challenge to solar energy applications in China, especially to solar PV power development, because the areas with abundant solar resources are far away from where the power load centers are located [7].

2.2. Energy demands

In the last 30 years, China's annual GDP has been increasing at an average rate of over 9%, which makes the energy consumption grow rapidly. China's primary energy consumption grew from 2586.8 million tons of coal equivalent (Mtce) in 2006 to 3478.0 Mtce in 2011 [8], increasing by 34.5% in the 5 years. Meanwhile, China's primary energy production grew from 2321.7 Mtce in 2006 to 3130 Mtce in 2011, increasing by 34.8% in the 5 years. On average, energy import accounted for 11% in the 5 years. Table 2 shows China's energy production and consumption [8–11], from which it can be seen that China's electricity demand had increased by 66% in

Table 1
Distribution of regional solar energy resource by class.

Zone	Sunshine h/yr	Total solar radiation GJ/(m^2 yr)	Regions
I	3200–3300	6.70–8.37	Qingzang Plateau, north Gansu, north Ningxia, south Xinjiang
II	3000–3200	5.86–6.70	North Hebei, north Shanxi, south Inner Mongolia, south Ningxia, mid-Gansu, east Qinghai, southeast Tibet, south Xinjiang
III	2200–3000	5.02–5.86	Shandong, He'nan, southeast Hebei, south Shanxi, north Xinjiang, Jilin, Liaoning, Yunnan, north Shaanxi, southeast Gansu, south Guangdong, south Fujian, north Jiangsu, north Anhui
IV	1400–2200	4.19–5.02	Middle and downstream Yangtze River areas, part of Fujian, Zhejiang, and Guangdong
V	1000–1400	3.35–4.19	Sichuan, Guizhou, Chongqing

Table 2
Growth rate of energy production and consumption compared with growth rate of GDP.

Year	Growth rate of GDP (%)	Primary energy (PE) production (Mtce)	Growth rate of PE production (%)	PE consumption (Mtce)	Growth rate of PE consumption (%)	Electricity consumption (10^9 kW)	Growth rate of electricity consumption (%)
2001	8.3	1438.8	6.5	1504.1	3.3	1468.3	8.7
2002	9.1	1506.6	4.7	1594.3	6.0	1638.4	11.6
2003	10.0	1719.1	14.1	1837.9	15.3	1889.1	15.3
2004	10.1	1966.5	14.4	2134.6	16.1	2173.5	15.1
2005	11.3	2162.2	10.0	2360.0	10.6	2477.9	14.0
2006	12.7	2321.7	7.4	2586.8	9.6	2824.8	14.0
2007	14.2	2472.3	6.5	2805.1	8.4	3245.8	14.9
2008	9.6	2605.5	5.4	2914.5	3.9	3426.8	5.6
2009	9.2	2746.2	5.4	3066.5	5.2	3659.5	6.8
2010	10.4	2969.2	8.1	3249.4	6.0	4192.3	14.6
2011	9.2	3130.0	5.4	3478.0	7.0	4692.8	11.9

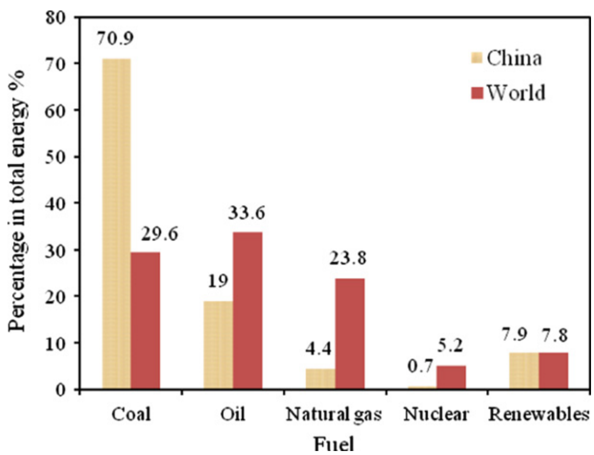

Fig. 1. Primary energy consumption by fuel.

the past 5 years. From the long-term perspective, the conventional power is not able to meet the increasing electricity demand. It is expected that the rapid development of renewable energy power, including PV power, can fill in this gap.

Global energy consumption grew by 5.1% in 2010 and 2.5% in 2011 [12], while China's energy consumption grew by 6.0% in 2010 and 7.0% in 2011. Fig. 1 shows the primary energy consumption by fuel in 2010. It can be seen that oil is the leading fuel in the world, while coal is the leading fuel in China. Coal accounted for more than 70% of energy consumption in China, and this number varied little in the past decade. China's coal-fired power plants are facing enormous pressure due to the rising prices of the fossil fuel and the increasing worry about environmental issues.

China aggressively implements its national solar mission due to energy safety and environmental conservation challenge. The 12th Five-Year Plan increased China's photovoltaic (PV) installation target from 10 to 15 GW by 2015 and to 50 GW by 2020. This is a powerful force to accelerate solar PV development and applications in China. Although the PV power price is much higher than the conventional coal-fired power at the present, it has its own competitiveness in the long run.

3. PV technology and applications in China

3.1. Typical types of PV systems in China

There are two typical types of PV power generation systems in China: stand-alone system and grid-connected system [13,14].

A grid-connected PV system consists of a PV array, an inverter, and a controller (Fig. 2). It converts solar energy directly into

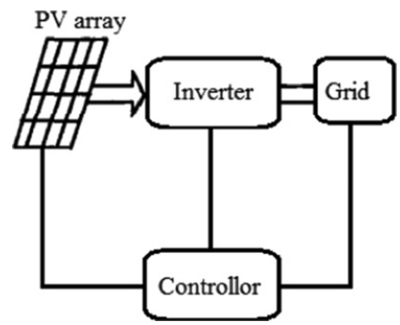

Fig. 2. Grid-connected PV power systems.

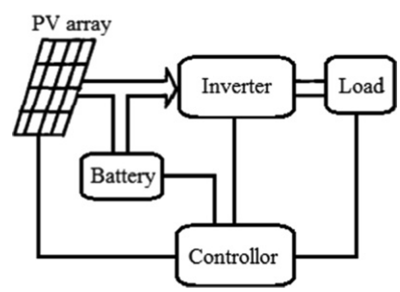

Fig. 3. Stand-alone PV power systems.

electric power, and supplies the electricity to a grid through an inverter. Grid-connected PV systems are generally used in very large scale PV power generation or in combination with buildings.

A stand-alone PV system consists of a PV array, an inverter, and a controller, and it usually has a storage battery (Fig. 3). Without a storage battery, the stand-alone PV system generates electricity and uses it directly, and thus it does not have ability to supply electricity without sunlight. Most stand-alone PV systems in China have battery. Nowadays, these PV systems are commonly used in small household PV units, PV power stations, lighting systems, and communication bases, with a demand of at least 3–4 MWp every year in remote, non-electrified regions in China, and PV lighting systems are already widespread in China.

3.2. Status of PV industry in China

China's PV industry grows rapidly, and a PV industrial chain has already formed. In 2007, the production of PV cells exceeded Germany and Japan, and China is the biggest PV cell producer in the world since then. The new installed capacity of China's PV power reached 2.2 GW in 2011, the first time it attained the gigawatt scale, making China the third largest country in PV

installations after Italy and Germany. It is estimated that China's PV installations in 2012 can reach 4.5 GW, reaching 14% of the global total.

The annual production and annual installation of PV products in China is shown in Table 3 [15–18], from which it can be seen that the PV industry in China is export-dominated, and the demand in the domestic market increases dramatically but is still insufficient.

The situation is changing and the domestic PV market is growing rigorously since the launch of the golden solar program in 2009 initiated by MOF and MOST [4]. This program aims to install more than 500 MW PV modules, including Feed-in-Tariff for building integrated PV (BIPV) systems, large scale grid-connected PV stations, as well as a support fund for research and development in PV industry. China has begun to implement policies to expand the domestic solar PV demand, including direct grants for solar PV installations.

The comparison of China's PV products with global PV products is listed in Table 4. It can be seen that China's domestic demand of PV products has increased rapidly, though about 90% of the PV products were exported overseas. Compared with 2010, both new PV installations and accumulated PV installations in China in 2011 doubled their shares in the world, increasing from 3% to 7.9% and from 2% to 4.5% respectively. According to NPD Solarbuzz [19], China consumed 33% of the global shipments in Q4 of 2012.

Among China's PV installations, grid-connected PV systems received rapid gain. In implementing the golden solar program, there were 294 grid-connected projects with capacity of 642 MW approved before 2011, indicating the rapidly expansion of the domestic grid-connected PV market in China. The grid-connected PV systems only accounted for 5% of the total PV installation capacity [20] in 2006, and the share increased to over 80% in 2011.

Table 5 shows the breakdown of the cumulative PV installation in China, where BIPV means building integrated photovoltaic and BAPV stands for building attached photovoltaic. The large scale PV plants and BIPV systems develop very fast. The largest large-scale PV plant is 20 MW in Xuzhou, and there were more than ten 10 MW PV plants in China in 2011. The largest BIPV system is the Shanghai world expo system, which is 3.13 MW.

In 2011, among the global top 10 solar PV cell manufacturers, which controlled about half of the global production, six were based in mainland and three in Taiwan, China, as shown in Table 6 [21]. Currently, more than 50 solar cell and over 300 solar module companies exist in China. China has extensive quartz sand and silica deposits, and can therefore manufacture the special-purpose materials and hardware for the rapid development of its PV industry.

3.3. Solar PV technology level and price in China

The overall Chinese PV technology still lies at a low level and most enterprises lag behind the world advanced level in the conversion efficiency of solar cells and modules (Table 7) [16]. China also falls behind other leading countries in research into the new and efficient solar modules and high pure silicon, thin film and high concentrated PV battery technologies.

Table 4
Comparison of China's PV products with global PV products (GWp).

	2010			2011		
	World	China	China's share (%)	World	China	China's share (%)
Annual production	20.5	10.5	51.2	50	21	42
Annual installation	16.6	0.5	3.0	27.7	2.2	7.9
Cumulative installation	39.7	0.8	2.0	67.4	3.0	4.5

Table 5
Breakdown of cumulative PV installation in China.

Market	2009		2010	
	Amount (MWp)	Share (%)	Amount (MWp)	Share (%)
Rural electrification	58	19.3	75	9.4
Communication and industry	40	13.3	42	5.3
PV products	40	13.3	40	5.0
BIPV/BAPV systems	73.1	24.4	256	32.0
Large scale PV stations in the Gobi/desert	88.9	29.6	387	48.4
Total	300	100	800	100

Table 6
2011 global top ten solar PV cell manufacturers by capacity [21].

Rank	Manufacturer	Country	Capacity (MW)	Founded
1	Suntech	Mainland China	2400	2001
2	JA Solar	Mainland China	2100	2005
3	Trina Solar	Mainland China	1900	1997
4	Yingli Green Energy	Mainland China	1700	1998
5	Motech	Taiwan China	1500	1981
6	Gintech	Taiwan China	1500	2005
7	Canadian Solar	Mainland China	1300	2001
8	Neo Solar Power	Taiwan China	1300	2005
9	Hanwha Solar One	Korea	1100	2004
10	JinkoSolar	Mainland China	1100	2006

Table 7
Solar cell efficiency [16].

Type of PV cells	Maximum efficiency in laboratory (%)		Commercial maximum efficiency (%)	
	China	International	China	International
Mono-slicon PV cells	20.4	25	19	22
Poly-crystalline Si PV cells	18	20.3	16	16.9
GaAs PV cells	29.25	42.3		> 26
CIGS PV cells	14.3	20.3		15.7
CdTe PV cells	13.38	16.7		8–10
Fuel-sensitized PV cells	8.1	11.1		
HIT	17.27	23		

Table 3
Annual production and annual installation of PV products in China (MWp).

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Annual production	4.5	10	10	50	200	400	1088	2600	4011	10500	21,000
Annual installation	4.5	12	10	10	8	10	20	40	160	500	2200
Cumulative installation	30	42	52	62	70	80	100	140	300	800	3000

As to product lines, China's PV manufacturers mostly imported their major equipment from Europe, the United States or Japan, which makes it very difficult for their products to compete with those of developed countries in the high-end market in the near future.

The PV module price decreased by 90% in the past 10 years from 2002 to 2012. The decline of the module price became steeper from 2008, mainly because of the sudden decrease of global market demand caused by serious export environment, such as the global financial crisis, a sharper cut back of the feed-in tariff in Germany, and the double remedies in America's concurrent imposition of antidumping and countervailing duties against China. The PV module price reduced to 0.55–0.91 US dollars in the end of 2012.

Currently, the cost of PV power generation is still too high to compete with the conventional electricity. Even after adjustment for its timing and transmission advantages, and the benefits of greenhouse gases mitigation, the social benefits of PV power are still smaller than the social costs in China. For example, for solar PV power generation projects which approved on July 1, 2011 or later, and approved before July 1, 2012 but not put into operation before the end of 2012, the feed-in tariff was set as 1.0 Yuan RMB/kWh, except Tibet, where the tariff continues to be 1.15 Yuan RMB/kWh. This price is much higher than that of conventional electricity.

China's solar PV industries still earned well margin and got noticeable expansion in 2012, which partly benefitted from the government policies and subsidies.

4. Solar thermal technology and applications in China

4.1. Solar water heater

4.1.1. Market constituent of solar water heater

There are three main categories of hot water heaters in the Chinese market: electric water heaters, gas water heaters, and solar water heaters (SWHs). The SWH is competitive and has become an attractive industrial sector in China. According to Huicong Research [22], SWHs share 22% of China's hot water heater market (Fig. 4).

About 70% of hot water heaters are sold to the countryside, where the ownership rate of solar hot water heaters amounts to 90% and those of electric hot water heaters and gas hot water heaters share 7% and 2%, respectively [23,24].

4.1.2. Production and cumulative capacity of SWH

Figs. 5 and 6 show the SWH annual production and cumulative capacity status from 2000 through 2011, respectively [25–28]. On average, the production capacity increased by 22% each year from 2000 through 2005, and about 27% each year from 2005 through 2010. In 2011, the SWH production reached 57.6 million square meters, and the cumulative capacity amounted to 194 million square meters. China has become the biggest SWH market in the world, holding about 2/3 of the cumulative capacity.

In 2010, there were about 5000 companies that develop, manufacture, sell, and/or install SWHs, with about 3.5 million employees.

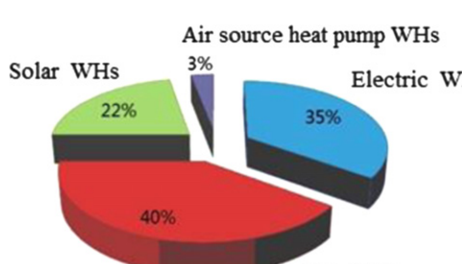

Fig. 4. Water heater shares in China's market.

4.1.3. Market structure of SWH

There are three dominant SWH types in Chinese market: batch, flat-plate, and vacuum tube types, of which the vacuum tube type has the largest market share (Fig. 7). In 2007, 95.35% of SWHs in China were vacuum tube systems and only 4.65% were flat-plate type [29]. This is contrast to the situation in the EU, where 85.58% were flat-plate systems and only 8.74% were vacuum tubes [30].

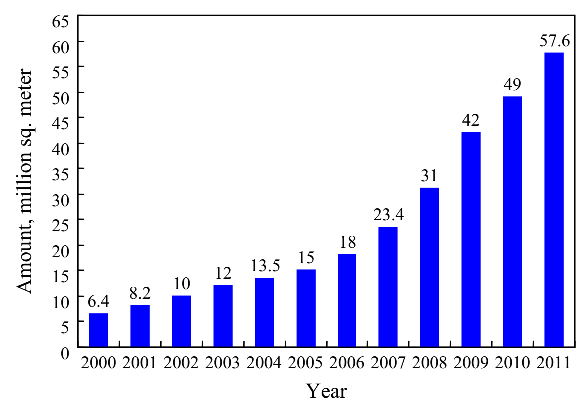

Fig. 5. Production of solar water heaters.

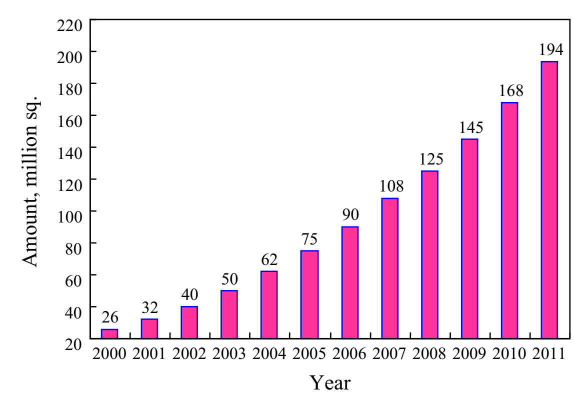

Fig. 6. Cumulative capacity of solar water heaters.

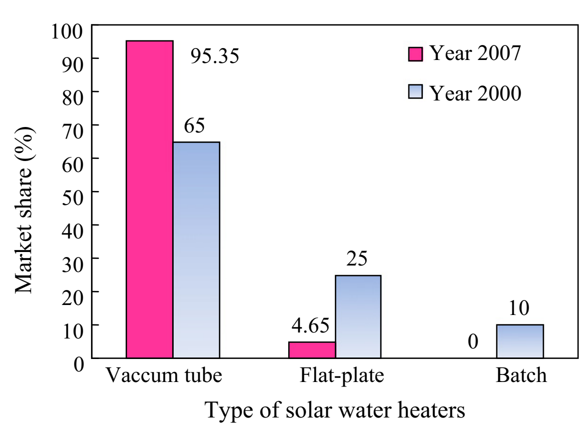

Fig. 7. Share of solar water heaters in China's market.

4.1.4. *SWH installation*

There are two main solar water installation styles in China: rooftop style (Figs. 8 and 9) and balcony style (Fig. 10). Fig. 8 shows a typical installation style, in which the SWHs were placed on the rooftop. Fig. 9 shows another commonly-seen rooftop installation style, where the SWHs were embedded into the roof of the building.

Fig. 10 shows a building in the Beijing Olympic Center, a demonstration project for new energy utilizations, where the SWHs were integrated with the building balconies. With proper design and installation, the SWHs integrated with the building can provide not only the service hot water, but also heat for the space heating in winter.

Fig. 8. Typical solar heat water system on rooftops in China [31].

Fig. 9. Solar heat waters embedded into the roof of the building [32].

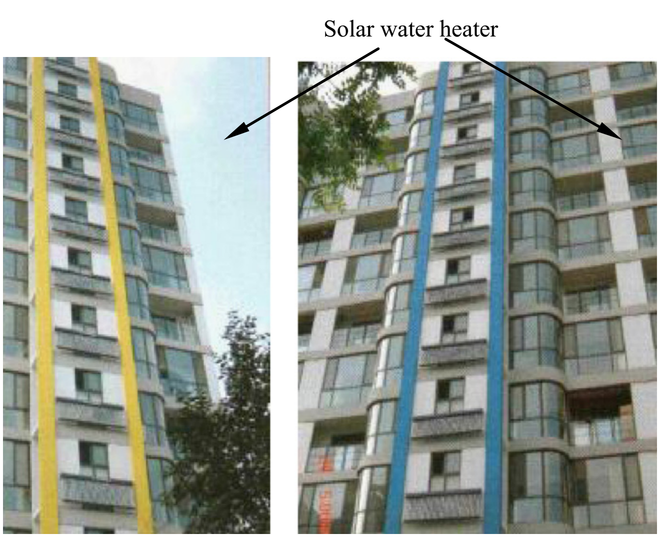

Fig. 10. Energy demonstration building in the Beijing Olympic Center.

4.2. *Solar building*

4.2.1. *Passive solar heated building*

China's first passive solar heated building (PSHB) was built in Mingqin County, Gansu, in 1977 [33]. PSHB experienced the fastest growing period from 1991 to 1995, at an annual growing rate of 54.5%. The growing rate became much slower after 2000, only 1.4%, as shown in Fig. 11 [34–36]. One of the main reasons for the slow growth is that the PSHB technology needs to be improved to lower construction costs for low incoming families and to increase comfort levels for the rich.

Traditional PSHBs use Trombe walls, direct gain windows, sunspaces or roof ponds. China developed several new types of solar energy collecting methods. Fang and Li [37] studied PSHB with lattice solar walls, as illustrated in Fig. 12. Another type found commonly in the Beijing area is the combination of direct gain windows with Trombe walls or lattice solar walls, with the direct gain window above the wall.

A number of cooperation programs and demonstration projects were performed in China. The earliest one is the China–Germany cooperation program, through which several PSHBs were built in a village of Daxing County, Beijing, for research and demonstration. In June 2004, the GEF program which provided funds for building 29 passive solar heated hospitals distributed in the rural areas in Shanxi, Gansu, and Qinghai were successfully completed. The total building area was 7860 m^2.

Most PSHBs can save 60–80% of the heating energy compared with the normal houses. The first cost of the PSHB usually increases by 12–40%, and the pay-back time ranges from 3 to10 years [38].

4.2.2. *Active and hybrid solar building*

Active and hybrid solar buildings have grown fast in China in the past decade. Most new energy demonstration projects took advantage of several technologies, such as combining the PSHB with the SWH, PV, and/or heat pump subsystems (Fig. 9). The thermal utilization subsystems can provide energy for service water heating, space heating and cooling, while the PV subsystem provides electricity for lighting and household appliances.

The cumulative capacity of solar buildings, including passive, active and hybrid ones, reached 15 million square meters in 2005 [39], and was estimated at 20 million square meters in 2010 [26]. Considering the pure passive solar buildings grew little since 2005, it can be reasoned that on average the active and hybrid solar buildings have increased about 1 million square meters each year in China since 2005.

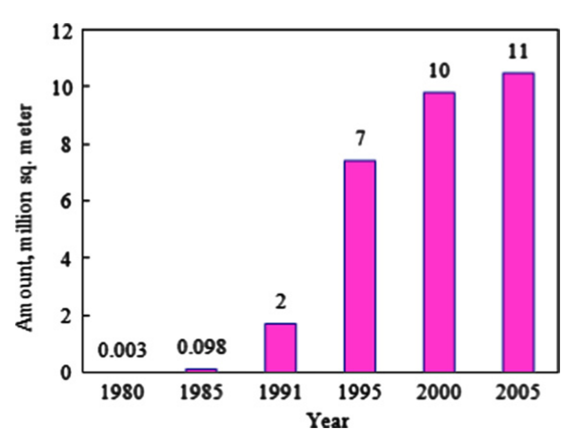

Fig. 11. Cumulative capacity of passive solar heating buildings.

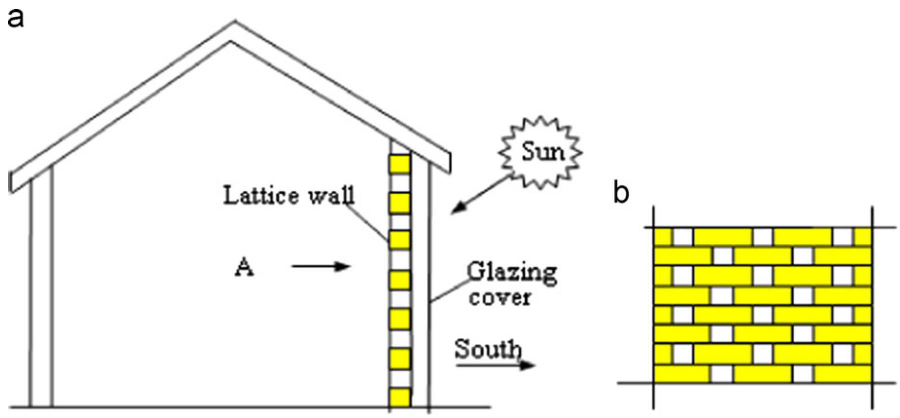

Fig. 12. Lattice wall and lattice solar wall heated building [37]. (a) Lattice solar wall heated building. (b) Lattice wall from view A.

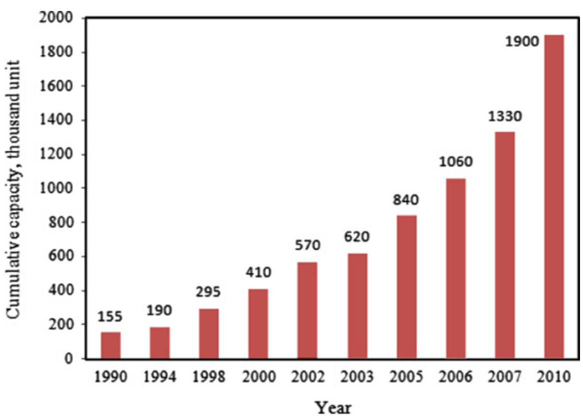

Fig. 13. Cumulative capacity of solar cookers in China.

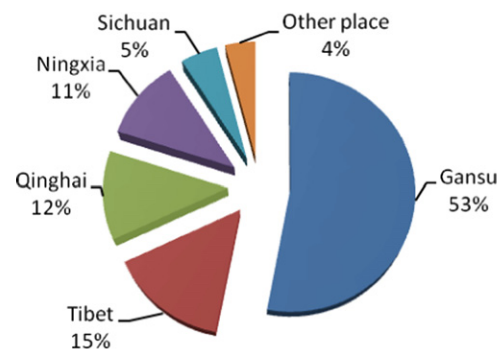

Fig. 14. Regional distributions of solar cookers in China.

4.3. *Solar cooker*

The cumulative capacity of solar cookers in China is shown in Fig. 13 [26,36,40–42]. There is a steady increase of 20,300 units each year from 1995. In most parts of China, solar cookers operate 150–200 days yearly. On average, one solar cooker can save firewood about 1000 kg/yr, getting back the investment within 1–2 years; each solar cooker has an area of about 2 m^2, priced at 60–80 US dollars.

Most of the solar cookers are used in Gansu, Tibet, Qinghai, and Ningxia provinces and remote mountain areas, where solar energy is abundant (Fig. 14).

5. Research and development of PV/T system in China

PV cells absorb up to 80% of the solar irradiation, among which only 5–20% is converted into electricity and the remaining energy becomes heat, resulting in PV laminates reaching temperatures as high as 35 °C above ambient temperature on sunny days [43]. As PV cells get hotter, they become less efficient, which can cause substantial decline in generating electricity. The most promising solution to this issue is the PV/thermal (PV/T) technology [44].

According to the circulating medium of the collector it contains, PV/T systems may be classified as PV/T air systems [45,46], PV/T liquid systems, PV/T heat pump systems, and PV/T heat pipe systems. The PV/T air system is less efficient than the other three categories, and it is also less complicated. Therefore, research activities for PV/T air systems are relatively less in China.

A PV/T collector commonly consists of an absorber, a transparent cover, PV cells, a frame, and insulation. Usually a low-iron tempered glass is used as a transparent cover. The absorber surface is typically made of copper or aluminum, which is painted black or selectively coated. The absorber transfers the captured heat to the circulating medium, such as air, liquid (water or anti-freezing fluid), refrigerant, or heat pipe medium, directly or indirectly. The circulating medium in turn takes the heat to somewhere it can be stored or used, such as a hot water tank, a building space, or to the ground for later retrieval by heat pumps. The insulation acts as a barrier to reduce the loss of the absorbed heat to the environment.

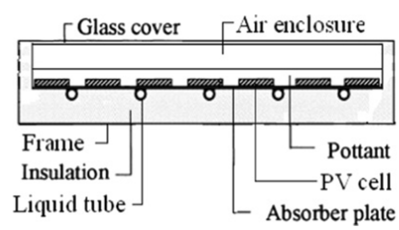

Fig. 15. PV/T liquid collector.

Most research activities of PV/T in China focus on PV/T hot water systems and PV/T heat pump systems.

5.1. *PV/T liquid system*

Fig. 15 shows the cross-sectional view of a PV/T liquid collector. The absorber transfers heat to the liquid that flows through the liquid tubes. The common used liquids are water and anti-freezing fluids. This heated hot fluid can be used to produce hot water or to heat a space [47,48].

According to the collector, a PV/T liquid system can be either a flat-plate system or a concentrating system. The flat-plate PV/T liquid system is simple in structure and easily combined with

buildings. A flat-plate collector may or may not have a cover. Studies of flat-plate PV/T systems are more than those of concentrating PV/T water heating systems. The following highlights flat-plate PV/T water heating systems, concentrating PV/T water heating systems and the effect of cover on performances of the PV/T water heating system.

5.1.1. Study of flat-plate PV/T hot water system

Wang et al. [49] summarized several factors which affect solar collector performances: cover optical performances, fluid mass flow rates, geometric properties, and PV cell efficiency. Geometric properties of a solar collector mainly refer to the length of absorber plate and the height of flow channels. It was found that increasing absorber plate length has little effect on cell efficiency but leads to the reduction of the thermal efficiency.

Cui et al. [50] established a two-dimensional dynamic model of PV/T system in natural cycle and simulated the system performance both on sunny day and cloudy day. The results showed that on sunny day, the average temperature of hot water in the tank gradually increased, and that the variation trend of electric power output was similar to that of solar radiation intensity, with the peak appearing slightly earlier than that of the solar radiation because the water temperature increasing caused the photoelectric efficiency to decline. During a year, the variation trend of PV efficiency was contrary to the intensity of solar radiation. It reached the lowest of 13.3% in June and the highest of 14.3% in December. On cloudy day, hot water temperature increased gradually, but the final temperature was about 20 °C lower than that on sunny day.

Ji et al. [51] designed a natural cycle PV/T experimental system with an aluminum alloy flat-plate solar water heater and conducted an all-weather outdoor experiment in Hefei, China. Evaluated with the primary energy saving criteria, the overall efficiency of the system was about 60%, noticeably higher than the thermal efficiency of the ordinary flat water heater and much higher than the efficiency of a PV system. Generally, the system could meet daily domestic hot water demand, producing hot water around 60 °C in sunny days and above 50 °C in most days. The electrical efficiency was 9.03–9.88%, and the average daily power generation was 0.46–0.53 kWh, which could meet the need of domestic lighting in rich solar irradiation areas.

Pei et al. [52] analyzed the effect of the glass cover on the PV/T system performance using the overall efficiency based on the first law of thermodynamics and the exergetic efficiency based on the second law of thermodynamics. The PV/T systems both with and without glass cover were simulated, with the mathematical model and calculation method described in [53]. The results showed that normally the system with cover was more efficient than that without cover.

5.1.2. Study of concentrating PV/T water heating system

Flat-plate PV/T systems are not cost effective. The high cost of PV systems is mostly associated with the PV cells, and this cost could be reduced by increasing the output per unit solar cell, which could be done by partly replacing expensive solar cells with a low cost optical material (concentrator). Concentrators commonly used are parabolic concentrator, dish parabolic concentrator, compound parabolic concentrator (CPC), parabolic trough collector, as well as Fresnel lens-type concentrator. The following briefly introduces the studies of parabolic trough concentrating PV/T water heating systems and CPC PV/T water heating systems in China.

Luo [54] analyzed the effect of tracking mode and solar intercept angle on the ideal trough parabolic mirror and presented the functional relation among the geometric concentration ratio of system, the relative aperture of concentrator, energy flux distribution and the rim angle. The year-around cosine values of incidence angles in single-axis tracking modes for Beijing, Shanghai and Kunming were calculated. The results showed that the cosine values of the incidence angle had nothing to do with the latitudes when adopting east-west horizontal axis tracking mode, and that the incidence angle changed a lot in spring and winter but little in summer and autumn.

Pei et al. [55] proposed a parabolic trough concentrating PV/T system and studied it numerically. The effects of east–west oriented and south–north oriented tracking modes, concentration ratio, water mass flow rates, as well as solar irradiation on the system performance were simulated using the spring and summer weather conditions of Hefei, China. The overall efficiency of the system was about 75%, while a conventional PV/T system only had 60–70%.

Cui et al. [56] designed and fabricated a flat mirror CPC with an aluminum heat-collecting plate having internal parallel flow channels. Single crystal silicon solar cells were attached to the upper surface of the heat-collecting plate to produce a PV/T collector. The PV/T collector was combined with the CPC, forming a concentrating PV/T system. The experimental results showed that the solar concentrating method decreased the electric efficiency of the PV module, but increased the total electric output, and that the overall energy efficiency evaluated by the primary energy saving [57] was above 70%.

Liu et al. [58] analyzed the thermal and electrical performance of a CPC PV/T system. The influence of some factors such as the dimension of the CPC PV/T system and the water mass flow rate on the performance of CPC PV/T system was investigated. The results showed that when the water mass flow rate was constant, the daily electrical and thermal efficiency decreased with the length of the CPC PV/T system increasing, and that when the length of the system was constant, the water temperature decreased and the system electrical efficiency increased with the water mass flow rate increasing. However, the change rate of the water temperature and the system electrical efficiency weakened with the water mass flow rate further increasing.

5.2. PV/T heat pump system

Fig. 16 shows a PV/T evaporator, the typical PV/T collector used in PV/T solar-assisted heat pumps (PV/T SAHP) [59,60]. The evaporator is the function part of the heat pump that is a compression vapor cycle machine. The liquid refrigerant with low temperature and low pressure in the evaporator absorbs heat transferred from the absorber plate and then evaporates into low-temperature low-pressure vapor. The vapor is drawn by the heat pump compressor, where it is compressed into high-temperature high-pressure vapor and then sent to the condenser of the heat pump. In the condenser, the vapor gives off heat to the heat sink (a storage tank, or a hot water tank for instance) and then condenses into high-temperature high-pressure liquid. The liquid refrigerant passes through the expansion device of the heat pump, becoming

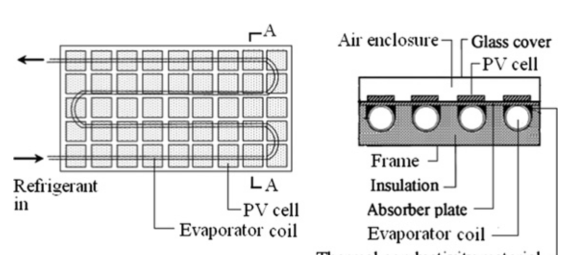

Fig. 16. PV/T evaporator.

low-temperature low-pressure liquid, and then enters the evaporator, repeating the cycle. With PV cells laminated on the front surface of the evaporator, the PV/T SAHP can acquire simultaneously thermal energy and electricity from solar radiation.

PV/T SAHP is the typical type of the PV/T heat pump studied in China. It is developed from direct-expansion solar-assisted heat pump technology, an attractive research spot in China in the past decade [61]. The advantage of the PV/T SAHP system over the PV/T liquid system is that its PV evaporator is able to work at a low temperature range, which makes its PV conversion efficiency improved [62].

Pei et al. [63] built a PV/T SAHP prototype and test facility. The PV/T SAHP prototype was tested under different condensing temperatures. The results showed that the PV/T SAHP system achieved an average COP of 5.4 and an average PV efficiency of 13.4%, with the maximum COP up to 10.4, indicating that the system had excellent thermal performance and PV conversion efficiency.

Ji et al. [60] built a PV/T SAHP system and developed a dynamic model of the PV evaporator based on the distributed parameter approach. Given the instantaneous solar irradiance and ambient temperature, the numerical model is able to output the spatial distributions of refrigerant conditions, including pressure, temperature, vapor quality and enthalpy. The experiment was carried out to test the actual performance and to verify the numerical model. The verification showed that the model was able to give satisfactory predictions. The experimental results showed that high electrical and thermal performance could be achieved. The PV efficiency was found to be above 12%, which is higher than that of the other types of PV/T systems.

Chow et al. [64] studied PV SAHP systems as an alternative for electric/gas water heaters in Hong Kong. Making use of a dynamic simulation model and the weather data of Hong Kong, they carried out the numerical analysis of a PV SAHP system. It was found that the proposed system with R134a was able to achieve a yearly-average COP of 5.93 and PV output efficiency of 12.1%, having energy output considerably higher than a conventional heat pump plus a PV "side-by-side" system. Therefore, it has promising application potential in Hong Kong.

Pei et al. [65] analyzed the effect of glazing cover on the performance of PV/T SAHP systems in winter. The results showed that using glass cover in winter reduced the PV efficiency but increased the photo–thermal efficiency and the system COP, and thus improved the performance of the PV SAHP system.

He et al. [66] studied the impact of PV cell coverage on the performance of a PV/T SAHP system. They found that when the coverage ratio of PV cells reduced, the heat gain of the system increased, while the output power of the system decreased. Overall, increasing the coverage ratio of PV cells made the system performance improved.

The supply of a PV/T HP and the demand of the users are not consistent for PV/T HP with a fixed speed compressor [67]. Generally, a PV/T HP system generates more power than the electric consumption at noon, but extra power supply is needed in morning and afternoon. In cold areas, a PV/T HP system cannot meet the hot water demands in winter but produces more hot water than needed in summer. This problem can be solved by using a variable speed compressor [59].

Wang et al. [68] studied experimentally the effect of an electronic expansion valve on the performance of a PV/T SAHP system. The variation of the system COP, collector efficiency, power generation, and condensation pressures with the opening of the electronic expansion valve was measured. It was found that the system COP decreased with the water temperature increase, and that the peak PV efficiency did not occur at the maximum solar irradiation. At a given opening of the electronic expansion valve, the compressor power began to vibrate with the solar irradiation increase, and the vibration became more apparent at the maximum opening. Based on the experiments, they proposed a stability principle for PV/T SAHP systems.

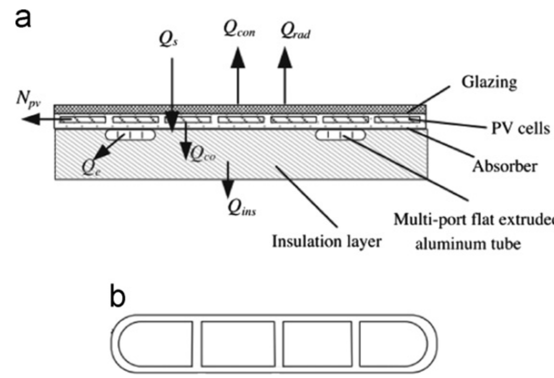

Fig. 17. Modified PV/T evaporator and the heat transfer process [59]. (a) Schematics of heat transfer in the modified PV/T C/E. (b) Multi-port flat extruded aluminum tube.

Xu et al. [59] proposed a new PV/T SAHP system and studied it numerically. The system had a modified PV/T evaporator that uses multi-port flat extruded aluminum tubes (Fig. 17). The simulation with the weather data in both Nanjing and Hong Kong, China, showed that the proposed system could efficiently generate electricity and thermal energy simultaneously in both cities all-year-round. Compared to the PV/T SAHP system with a conventional PV/T evaporator using round copper tubes, the new system increased COP by 7%, thermal efficiency by 6%, and relative electrical efficiency coefficient by 2%.

6. Conclusion and discussion

6.1. Summary of status of solar energy development and applications in China

China is abundant in solar energy resources and has become the biggest solar production, sale and consumption country in the world. The Chinese government has formulated a series of laws and regulations to stimulate renewable energy applications in the past 10 years, especially PV technology, SWHs, solar buildings, and PV/T systems.

A number of cooperation programs and demonstration projects of solar PV, solar thermal, and PV/T applications were performed. Most new energy demonstration projects made use of several technologies, combining PSHB with SWH, PV, and/or heat pump subsystems, with the thermal utilization subsystems providing energy for service water heating, space heating and cooling, and the PV subsystem providing electricity for lighting and household appliances.

China is the biggest PV cell producer in the world since 2007. The new installations of PV products reached 2.2 GW in 2011, which makes China the third largest country in terms of PV installed capacity. Among the PV installations, grid-connected PV systems received rapid gain, holding the share over 80% in 2011.

Among the solar thermal utilizations in China, SWHs get the most popularity, with the cumulative installations constituting about 2/3 of that in the world. Now, the SWH is competitive in Chinese hot water heater market, holding about 22% share. One trend in SWH development is the integration of the SWHs with the building structure.

The heat rejection of PV cells can cause a substantial decline in generating electricity during hot sunny day. The most promising

solution to this issue is PV/T technology. Most research activities of PV/T technology in China focus on PV/T hot water systems and PV/T heat pump systems.

6.2. Problems lying in China's PV industry

Although China's PV industry is getting strong, problems exist in many aspects:

(1) China's PV industry is export-dominated, and thus is vulnerable to foreign policies and foreign markets, while foreign trade barriers to China's PV products are growing high. The domestic installations increased quickly but the share was still minor.
(2) The cost of PV power generation in China is way higher than conventional electricity, which makes the domestic consumption somewhat government-subsidy-dependant. Without government stimulation and support, it would have atrophied.
(3) China's PV technology lies at a relatively low level. The conversion efficiency of solar cells and modules from most enterprises lags behind the world advanced level. Besides, China falls behind other leading countries in research into new and efficient solar PV products.
(4) The major equipment of China's PV product lines was mostly imported from foreign countries and is not the most advanced, which weakens China's PV products to compete with those of developed countries in the high-end market. On the other hand, It is a challenge for maintenance to ensure the stability and reliability of the equipment.
(5) The distribution of solar energy resources is significantly inconsistent with that of the power grid. Regions with rich solar energy resources are normally distant from the load centers, which requires costly power grid investments.

6.3. Suggestion

For solving the problems lying in China's PV industry, the following suggestions are proposed:

(1) The cost level of solar PV power generation determines the future of China's PV industry. The appropriate government subsidies for the PV industry in a given period of time is necessary. However, these subsidies should have strict subsidiary conditions for the enterprises' R&D investments and outputs, including efficiency improvement and cost reduction requirements. The government also needs to enlarge R&D investment to generate more innovations and new technologies in the PV industrial chain to lower PV power generation cost.
(2) Solar PV enterprises should increase their own R&D investment to quicken their steps in innovation and technological progresses so that their dependence on foreign technology can be quickly decreased and their competence and risk resistance capacity can be strengthened. Indeed, China's government tends to continue to subsidize its solar PV industry on some scale in the near future. However, the government-subsidy-dependent situation is not sustainable. Many governments, including the United States and Germany, are phasing out their subsidies.
(3) China has the biggest PV industry in the world, but is not strong enough in PV technology. There are some products surpassing foreign counterparts in technology. However, China's own manufacturing and equipment technology lags advanced countries. In order to compete with other countries in foreign markets, China needs its own strong manufacturing and equipment technology.
(4) China needs to continue to quickly increase domestic PV consumption. The heavy power load areas usually have very limited land sources for building solar PV power plants. The utilization of building roofs is a promising approach, where the combination of solar PV and thermal technologies can play an important role. It is expected that PV/T hot water systems will become one of the main solar systems in buildings in China.
(5) Facing increasing trade barriers from developed countries, China's PV enterprises should actively exploit new emergence foreign markets, such as the Middle East and Latin American.

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